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Bed Form Development and Distribution Pattern, Parker and Essex Estuaries, Massachusetts

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Velocity, depth, temperature, grain size, and bed form scale and orientation were measured for complete tidal cycles at 50 stations in two New England estuaries. Scuba observation of bed form change and migration, fathometer profiles, and 700 bed form scale and orientation readings were also carried out. This investigation led to the recognition of a sequence of bed forms based on increasing "flow strength."

Bed form type is governed by maximum flood and ebb velocities ($\bar{U}$max) attained at a given locality. Velocity asymmetry and duration are important

20. Abstract (Continued)

in determining bed form morphology and amount of crossbedding bimodality. Froude number (Fr) shows good correlation with bed form type only in depths less than 2 meters.

In the intertidal and shallow subtidal (<2 meters MLW) zone, sand waves are characterized by Umax 80 centimeters per second, large velocity asymmetry (Fr = 0.15-0.25), planar crossbedding, little crossbedding bimodality, and dominant flood orientation. Cuspate megaripples are characterized by Umax 80 centimeters per second, small velocity asymmetry (Fr = 0.25-0.4), festoon crossbedding, high crossbed bimodality, and no dominant orientation. In deep subtidal (>2 meters MLW) areas, sand waves are the principal bed form. They show no dominant orientation. However, where Umax exceeds 80 centimeters per second, megaripples are superimposed on the sand wave form and crossbedding is complex.

PREFACE

CERC is publishing this report because of its interest and value to coastal engineers.

This report was prepared by Jon C. Boothroyd and Dennis K. Hubbard of the Coastal Research Center, Department of Geology, University of Massachusetts. Work was done under Contract No. DACW 72-70-C-0029 with CERC; partial field support was provided by Contract No. N00014-67-A-0230-0001 with the Office of Naval Research (ONR), Geography Branch.

The barge used as a diving platform was built by Eugene G. Rhodes and James Terrell at the Coastal Research Center. Special appreciation is extended by the authors to Kerry Campbell and Martha Hubbard, who served as the deck crew and contributed greatly in making the diving method a success.

NOTE: Comments on this publication are invited.

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JAMES L. TRAYERS
Colonel, Corps of Engineers
Commander and Director

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BED FORM DEVELOPMENT AND DISTRIBUTION PATTERN, PARKER AND ESSEX ESTUARIES, MASSACHUSETTS

by

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and
Dennis K. Hubbard

I. INTRODUCTION

Bed forms, primary sedimentary structures and geometry of sand bodies in estuaries have been studied by the Coastal Research Center, University of Massachusetts, since 1965. (Coastal Research Group, 1969), (DaBoll, 1969), (Hartwell, 1970), (Farrell, 1970). Complete tidal-cycle velocity and depth data have been collected at over 300 hydrographic stations in 15 New England and Long Island estuaries by the Center. Extensive mapping of intertidal sand bodies with concurrent recording of type and orientation of bed forms was also carried out. Studies of the Parker River-Essex estuary area are discussed by Hayes, Anan, and Bozeman, (1969), and by the Coastal Research Group, (1969). This study continues their work and documents the development and migration of estuarine bed forms in response to complex flow patterns and to differences in intertidal and subtidal topography.

The study area is located in the southern part of the Merrimack embayment on the northeastern Massachusetts coast. (Figure 1.) Figure 2 is an aerial oblique view, taken at low tide, looking southeast over the study area. Mean tidal range in the area is 2.6 meters, or *mesotidal* in the classification system of Davies (1964).

Discussion in this report is limited to the lower Parker River intertidal sand bodies and subtidal channels and the flood-tidal delta of the Essex estuary. Description of various topographic forms of flood-tidal deltas and adjacent channels follows the classification of the Coastal Research Group (1969). Figures 3 and 4 illustrate these forms as applied to the Parker and Essex estuaries.

II. FIELD METHODS

1. Diving Barge

In an attempt to improve correlation of tidal-current velocity and depth parameters with bed form type, orientation, and migration habit, a program was developed that allowed divers to make bottom observations while velocity and depth measurements were being recorded. A stable diving platform (barge) was designed for work in current velocities up to 150 centimeters per second and water depths to 7 meters.

The barge used as a stable diving platform is a 10-by 16-foot open platform with a 2-by 4-foot center hatchway. (Figure 5.) Flotation is by Styrofoam billets; the barge draws 4 inches of water. A tetrapod frame straddles the hatchway and it in turn supports an 8-foot-long boom. A 3-by 5-foot, weighted, slatted staging assembly is suspended 3 feet below deck level under the hatchway.

Diver movement to and from the water is through the center hatchway. The staging serves as an underwater access point to the barge. A diver can remain on the staging in up to

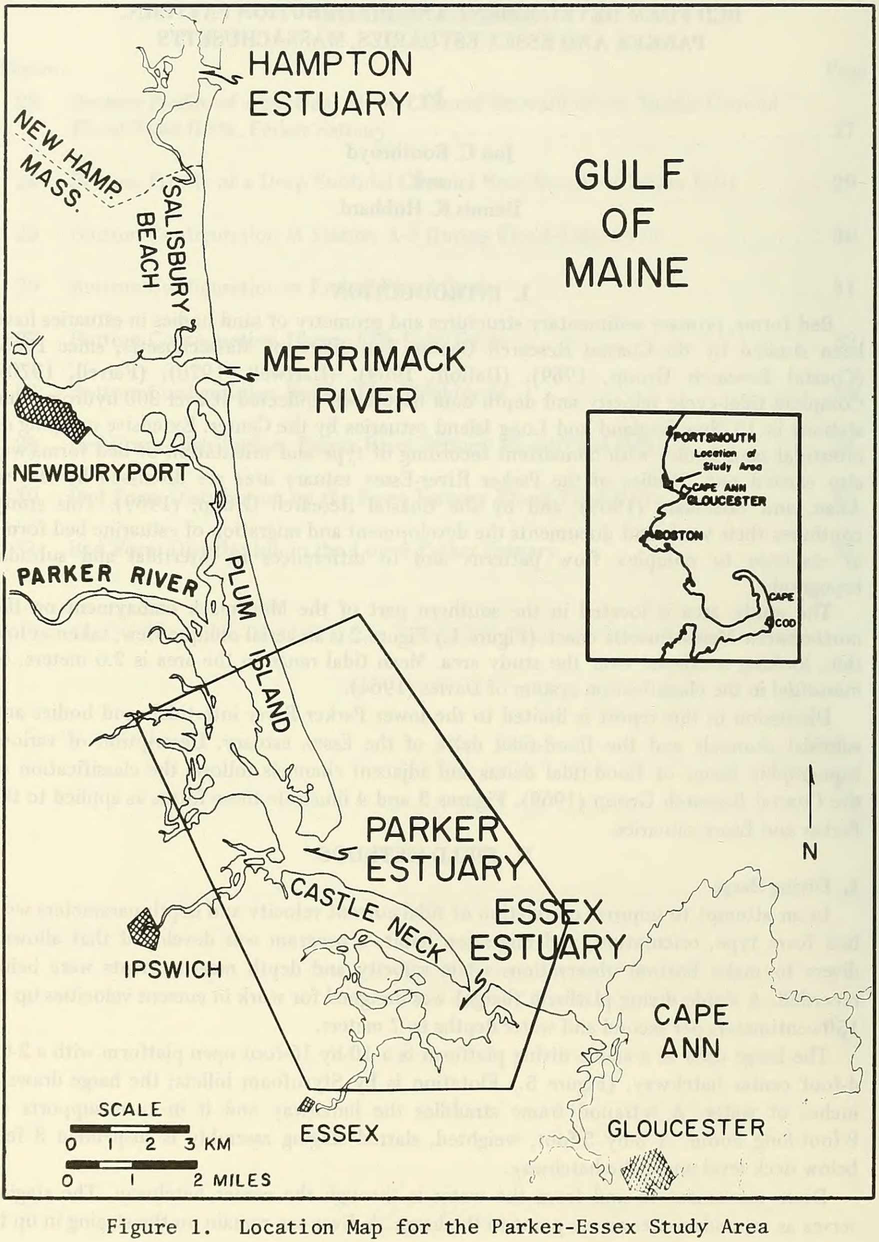


Figure 1. Location Map for the Parker-Essex Study Area

Figure 2. Aerial Oblique View Looking Southeast Over the Lower Parker River Estuary. Middle Ground flood-tidal delta complex is at the lower left; swash bars of the ebb-tidal delta are at top center. Plum Island, a barrier island, is at left center; Castle Neck barrier spit is at upper right. Profile line near mouth of Parker River is detailed in Figure 24.

Figure 3. Aerial Oblique Photo of Middle Ground Flood-Tidal Delta Complex. View is northwest up the Parker estuary; flood-tidal current direction is from bottom to top of photo. Topographic forms numbered are: (1) ebb shields, (2) ebb spits, (3) spillover lobes, (4) clam flat, (5) marsh, (6) flood channels, and (7) ebb channels.

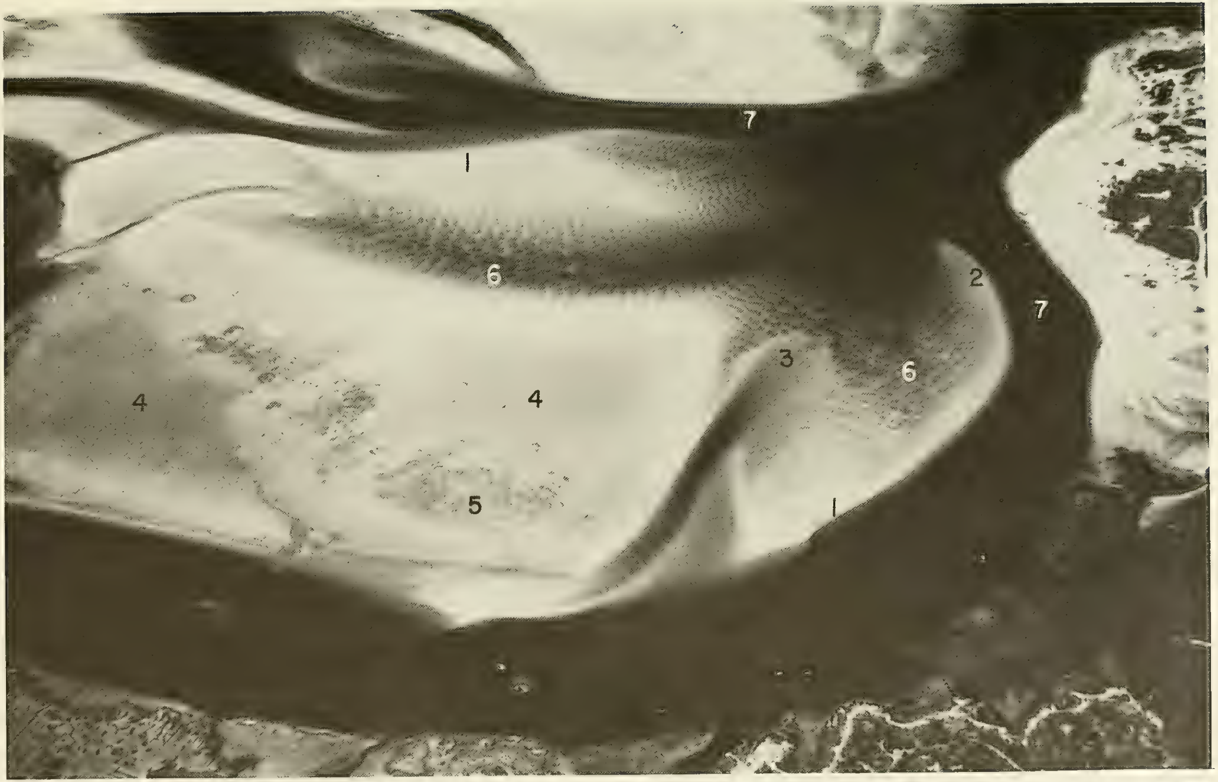


Figure 4. Aerial Oblique View of the Flood-Tidal Delta Complex in the Essex Estuary. Inlet mouth is to the right. Topographic forms numbered are: (1) ebb shields, (2) ebb spits, (3) spillover lobes, (4) clam flat, (5) marsh, (6) flood channels, and (7) ebb channels.

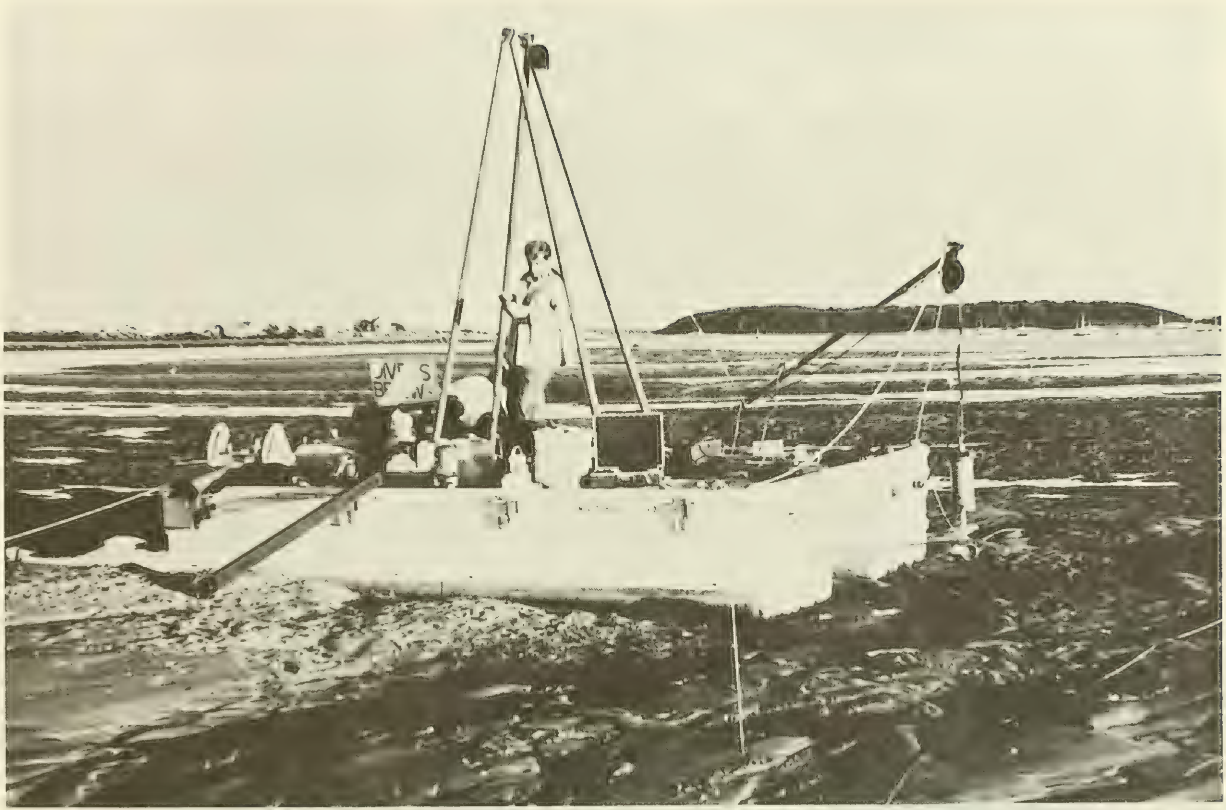


Figure 5. Diving Barge at an Intertidal Station. Note the central tetrapod frame and the boom supporting a current meter.

6-foot seas without danger from movement of the barge. The hatchway also affords the diver an excellent means of boarding and leaving the barge deck without damage to his equipment and without interfering with other workers on the deck.

The barge was held in position by a four-point mooring system from each corner of the barge. A separate line extends from the underwater staging to the bottom station for easy diver movement from the barge.

2. Bottom Rope Support System

A diver in full scuba gear can swim for a short time at a maximum of 50 centimeters per second. Since current velocities of 75 to 100 centimeters per second were common, and velocities up to 250 centimeters per second were possible, the diver needed a support system. A series of aluminum pipes, 125 centimeters long and 3 centimeters in diameter, were placed about 75 centimeters deep and 10 meters apart in a line in the direction of current flow. A 3/8-inch nylon rope was run from pipe to pipe. A rope grid system was constructed when two rows of pipes were used. Fifty to seventy meters of line were thus constructed with a 10-meter trailing rope at the downcurrent end of the system. The line from the barge was attached at the upcurrent end of the system. A small dinghy, anchored 50 meters downcurrent of the last pipe, acted as an emergency station if a diver was swept past the last pipe. The diver is propelled down the rope system by the current, using the rope as a guide. He moves hand-over-hand along the rope in a upcurrent direction. The pipes provide convenient resting points, and, if an elbow is hooked around the pipe, a hand is free for other work. Figures 6 and 7 illustrate the complete barge-rope support system.

The rope support system enabled the crew to work reasonably well in current velocities up to 100 centimeters per second and with difficulty in velocities up to 150 centimeters per second. Moving along the bottom is not difficult at this increased velocity, but fluid drag tends to loosen diving equipment (e.g., face masks) and hand-held gear can be torn from the diver's grasp. A 1.75-inch-diameter rope is recommended to reduce hand fatigue.

3. The Greer Compass Case

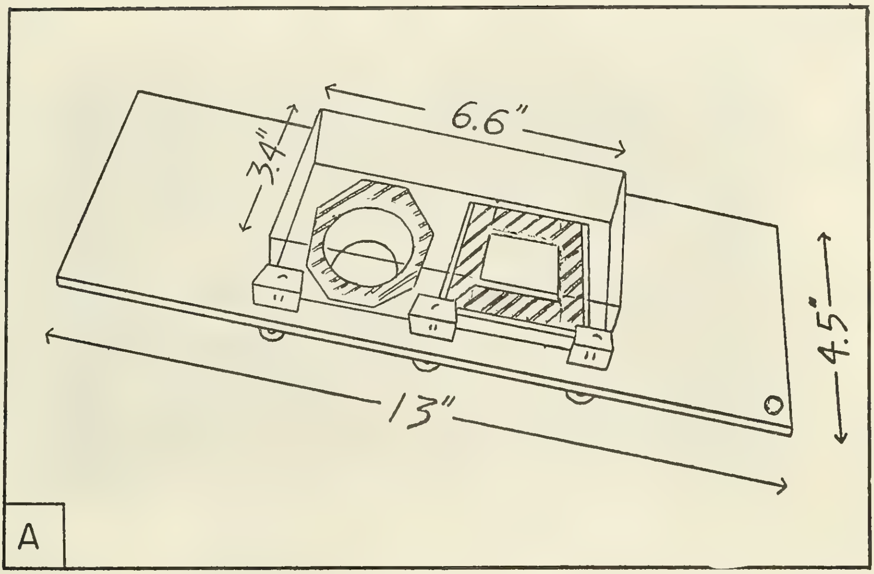
An accurate device to take underwater measurements of slipface azimuths of bed forms was achieved by mounting a Brunton compass in a waterproof housing. The case, modified from a design by Sharon Greer, is constructed of 0.5-inch plexiglass. It is a simple and inexpensive means of converting a Brunton compass into a useful underwater tool. (Figure 8A.)

A clear box, with outside measurements of 1.35- by 6.6- by 3.4-inches, was machined to accept an O-ring seal and fitted to a 13- by 4.5-inch plate to form a watertight compass housing. Six 0.5- by 0.7- by 0.7-inch blocks were machined to accept 0.5- by 0.6-inch wing nuts. These blocks were fused to the front housing unit at regular intervals (corresponding to six holes in the backplate) to maintain a watertight seal.

A 2.8- by 2.8- by 0.5-inch plexiglass block was centered 8 inches from one end and fused to the backplate. The block supports the compass cover in an open position and helps steady the compass. A hole 2 inches in diameter and centered 5 inches from the same end, was cut next to this block for easy access to the clinometer arm. A cylinder was then machined to an inside diameter of 2.5 inches and placed over the hole in the backplate, and a 3-inch plate was fused to the cylinder. A 3/8-inch hole was drilled to accept an Ikelite camera control. (Figure 8B.) The shaft on the camera control was cut to 2 inches and joined to the clinometer arm by an adapter machined to fit over the arm. Finally, a 1/4-inch neoprene gasket was fitted over both the support block and the hole in the backplate to cushion the compass and to help hold it in place.

Figure 6. Pipe and Rope System in Place at an Intertidal Diving Station

Figure 7. Barge on the Crest of a Sand Wave. Long staff in center is a tide gauge. The pipe to the right of the gauge is part of the diver support system.



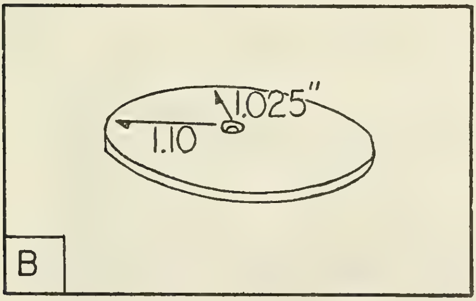


Figure 8. A. Diagram of the Greer Plexiglass Underwater Compass Case

B. Diagram Showing Specifications for Backplate, Modified to Facilitate Use of the Clinometer Arm

4. Study Methods

The barge was usually moored at the diving station the day before the station was to be occupied. Generally, current velocities were read over the crest of large-scale bed forms (sand waves), thus the barge was moored with the boom over a crest. Figure 7 shows the barge at an intertidal sand wave station. A 3-meter tide staff was placed near the barge for easy reading. (Figure 7.) At intertidal locations two staffs were used, one intertidal and one subtidal. Relative elevations of each were obtained by transit.

Four persons generally made up a diving station crew: 2 divers, a diver tender and a person to record velocity, depth, and temperature measurements. Tide gauge readings were taken every 7.5 minutes, and velocity, depth and temperature readings every 15 minutes. The divers also obtained velocity measurements from floats, and recorded depth over bed form crests with a simple scale.

III. BED FORM CLASSIFICATION

In this study, bed forms are classified by spacing: ripples, spacings less than 60 centimeters; megaripples, spacings from 60 centimeters to 6 meters; and sand waves, spacings greater than 6 meters. Figure 9 illustrates megaripples with superimposed ripples; Figure 10 shows sand waves with a spacing of about 14 meters. Klein (1970), in a study of Bay of Fundy intertidal bed forms, groups megaripples and small sand waves together as dunes and has a separate category for large sand waves. Allen (1968) makes no distinction between megaripples and sand waves, classifying both as large-scale ripples.

Glossaries by Allen (1972), and the U.S. Naval Oceanographic Office (1966), define megaripples and sand waves as the same bed form. A task force report on bed forms in alluvial channels, prepared for the Hydraulics Division, American Society of Civil Engineers (1966), uses the term sand wave to describe several bed form types, and megaripple is not included in their nomenclature. These bed form classifications are compared to the classification in this study. (see Table.)

As well as a spacing difference, megaripples are morphologically distinct from sand waves. Megaripples are characterized by sinuous to highly cuspate crests, usually with well-developed scour pits in front of the crests. Some megaripples have straight crests and scour pits occur at intervals along the crest. Megaripples also have a small spacing-to-height ratio in comparison with sand waves.

Sand waves have straight to sinuous crests; scour pits are absent or at best poorly developed. Sand waves, which have a large spacing-to-height ratio, are termed two-dimensional bed forms by some workers, whereas the megaripples are termed three-dimensional bed forms.

Heights and spacings of bed forms were measured on a 50-by 50-meter grid system for most of the intertidal parts of flood- and ebb-tidal deltas, and on two lines of measurement in subtidal flood channels. The results of the field measurements are plotted in Figure 11. Megaripples (solid circles) show a good grouping at spacings less than 6 meters, while sand waves (solid squares) show a wider spread of spacings. Sand wave spacings tend to concentrate at 11 to 16 meters. Megaripples appear to increase in height with increase in spacing, although there is much scatter. Sand waves show no height-spacing trend, nor do megaripples and sand waves when considered together. These two morphologically different bed forms, megaripples and sand waves, thus show a distinct spacing difference.

Figure 9. Megaripples on an Intertidal Sand Body, Parker Estuary. Ripples are superimposed on the megaripple form. Bed form spacing is about 2 meters.

Figure 10. Sand Waves on the Parker Estuary Flood-Tidal Delta. Spacing is about 14 meters.

Table. Bed Form Classifications

Source	Bed Form Types		
	Ripples	Megaripples	Sand Waves
Coastal Research Center (this study).	Spacings less than 60 centimeters.	Spacings 60 centimeters to 6 meters.	Spacings greater than 6 meters.
Allen (1972), "Glossary of Coastal Engineering Terms," CERC MP 2-72.	Small bed forms with wavelengths less than 1 foot, and heights less than 0.1 foot.	Same as sand wave.	Same as megaripple; a large wavelike sediment feature composed of sand in very shallow waters. Wavelength may reach 100 m; amplitude is about 0.5 meter.
American Society of Civil Engineers (1966), "Nomenclature for Bed Forms in Alluvial Channels."	Small bed forms with wavelengths less than approximately 1 foot; heights less than approximately 0.1 foot.	Not classified.	Not classified. Sand waves defined as synonyms under bed forms, ripples, bars, dunes, transition and antidunes.
U.S. Naval Oceanographic Office (1966), "Glossary of Oceanographic Terms."	Called *ripple marks*; undulating surface features of various shapes produced in unconsolidated sediments by wave or current action. As size increases, ripples grade into sand waves, sand ridges, sand dunes, and migratory sandbanks or shoals.	Same as sand wave; wavelength may reach 100 meters, and amplitude is about 0.5 meter.	Same as megaripple .

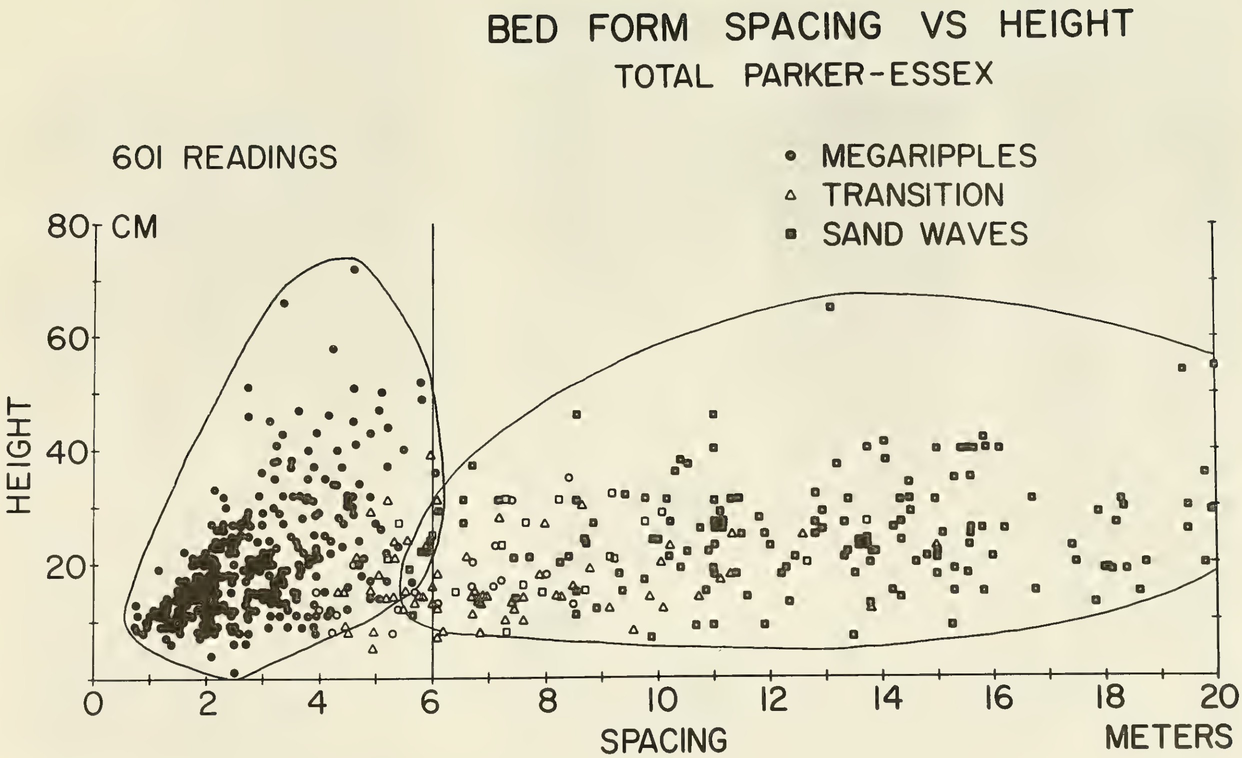


Figure 11. Height-Spacing Relationships for Intertidal Bed Forms in the Parker-Essex Estuaries. Lines define general fields for the occurrence of megaripples and sand waves.

Transition bed forms (Fig. 11) are concentrated around a 6-meter spacing. They occur in intertidal areas at margins of sand wave fields and at junctures between sand wave and megaripples zones. Transition bed forms resemble dwarfed sand waves, with straight crests, unable to fully develop in the hydrologic regime in which they formed. The spacing differences of all three types may be explained by differences in hydrodynamic conditions governing the formation and migration of the bed form.

IV. FLOW CONDITIONS

Current stations were occupied for a complete tidal cycle at over 60 intertidal and subtidal locations in both estuaries. Figure 12 shows the location of 16 stations near the Parker estuary flood-tidal delta complex. A segment of this flood-tidal delta can be used to illustrate the complex relationship of flow conditions to bed forms and topography. This segment, outlined in Figure 12, is shown in an aerial oblique view in Figure 13.

Megaripples, sand waves and a transition form (small ebb-oriented sand waves), were continuously monitored by divers at three intertidal diving stations. (Figure 13.) Depth and velocity measurements were recorded at 15-minute intervals. Velocity measurements were made over the crest of the bed form 30 centimeters below the surface. Repeated measurements show equal velocity values from the surface to 20 centimeters above the bed (limit of the ducted-rotor current meter).

Average velocity curves (Fig. 14) show that megaripples have a high maximum flow velocity (103 centimeters per second) and little or no velocity asymmetry; sand waves have a lower maximum flow velocity (78 centimeters per second) and large velocity asymmetry; and transition forms a lower maximum velocity (64 centimeters per second) and little velocity asymmetry.

Velocity asymmetry in New England estuaries is discussed by Hayes, Anan, and Bozeman (1969), on differences between sand flats and channels. The sand wave curve (Fig. 14) is a typical sand-flat curve but the megaripple curve, also from a sand-flat station, does not exhibit *typical* velocity asymmetry. This is due to its location on an ebb shield which will be discussed later.

V. BED FORM MIGRATION

Figure 15 illustrates velocity–bed form migration differences between megaripples and sand wave stations. Ripple migration begins at about 30 centimeters per second and megaripple migration at about 60 centimeters per second. Megaripples migrate during flood and then reverse and migrate in an ebb direction for an approximately equal timespan. Average megaripple migration rate is about 120 centimeter per hour (Fig. 16) and total ebb distance migrated was 450 centimeters. Significant migration occurs during falling velocities and water depths as the bed form emerges at the end of the tidal cycle.

Sand wave migration occurs only during a small part of the flood-tidal cycle and not at all on the ebb. (Figure 15.) Slipface migration begins at about the same velocity as megaripple-slipface migration, but flow over megaripples reaches a higher maximum velocity for a longer timespan. Intertidal sand wave migration measured for 3 months at stations on the Parker flood-tidal delta is shown in Figure 17. The stations are plotted in Figure 18. Migration during neap tides was 5 to 10 centimeters per tidal cycle while migration during spring tides (full moon) was 40 centimeters per tidal cycle. Hence, megaripple migration occurs at a rate 10 to 50 times greater than sand wave migration.

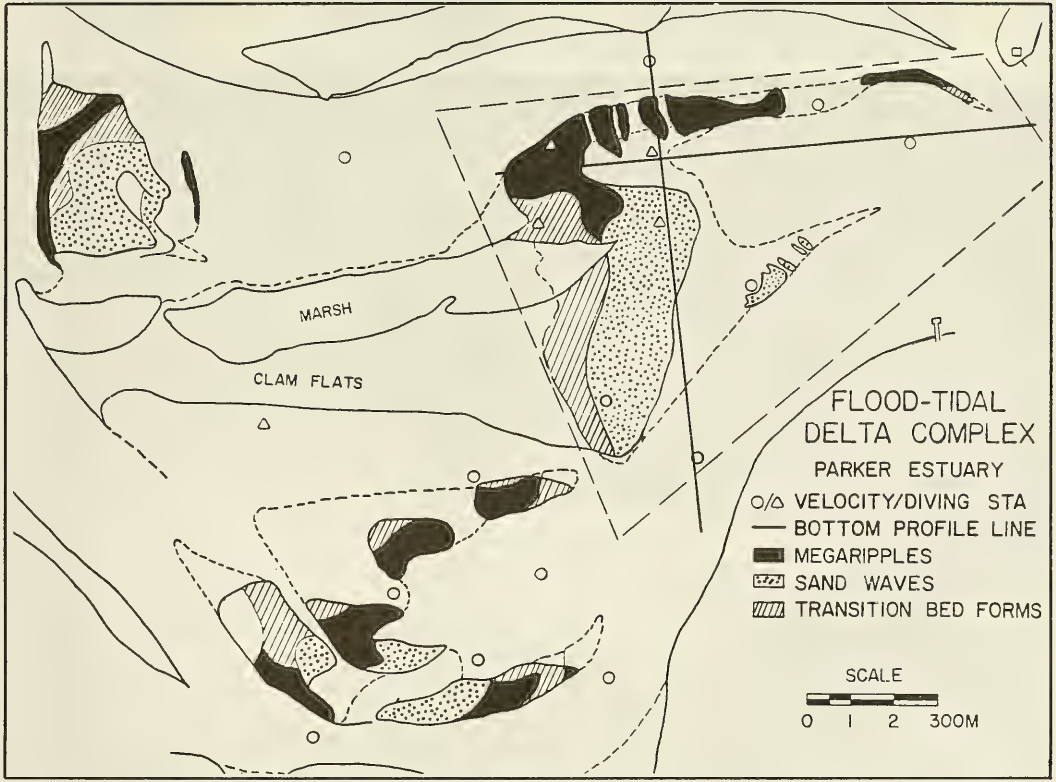


Figure 12. Location Map of Parker Estuary Flood-Tidal Delta Complex. Area outlined by dashed line is shown in detail in Figure 13. Patterns delineate distribution of intertidal bed forms.

Figure 13. Aerial View of a Part of Middle Ground Flood-Tidal Delta. Location of three diving stations are shown. Bed form morphology is: FL - flood-oriented sand waves, TR - transition bed forms, and MR - megaripples.

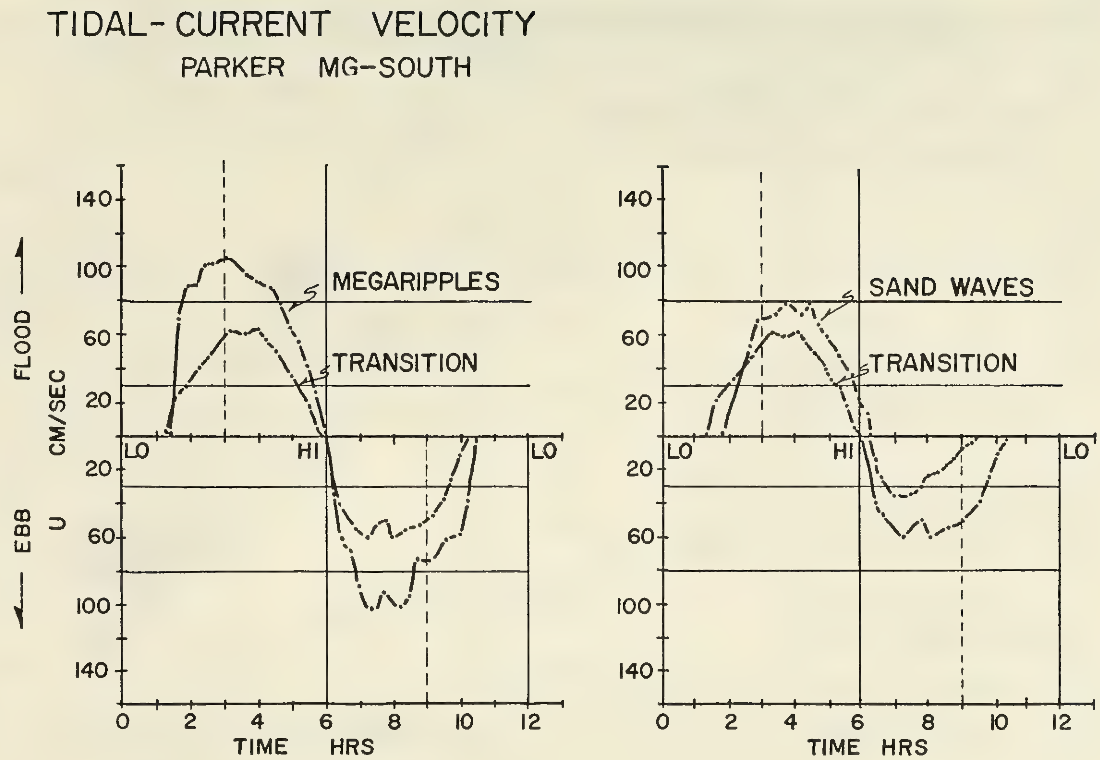


Figure 14. Velocity Curves for Megaripples, Sand Waves and Transition Bed Forms. (Parker, Middle Ground-South.) Measurements were taken at 15-minute intervals throughout a complete tidal cycle.

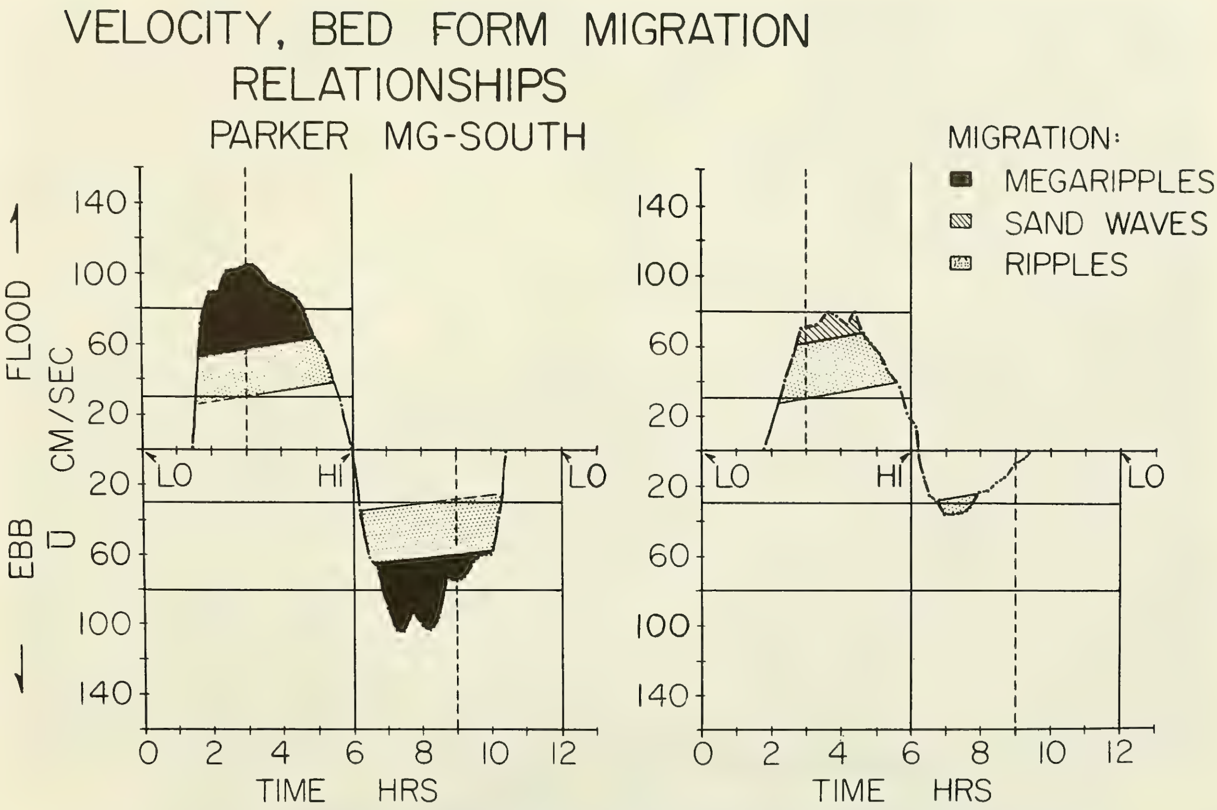


Figure 15. Bed Form Migration Habit for Megaripples and Sand Waves Measured Throughout a Complete Tidal Cycle. (Parker, Middle Ground-South.)

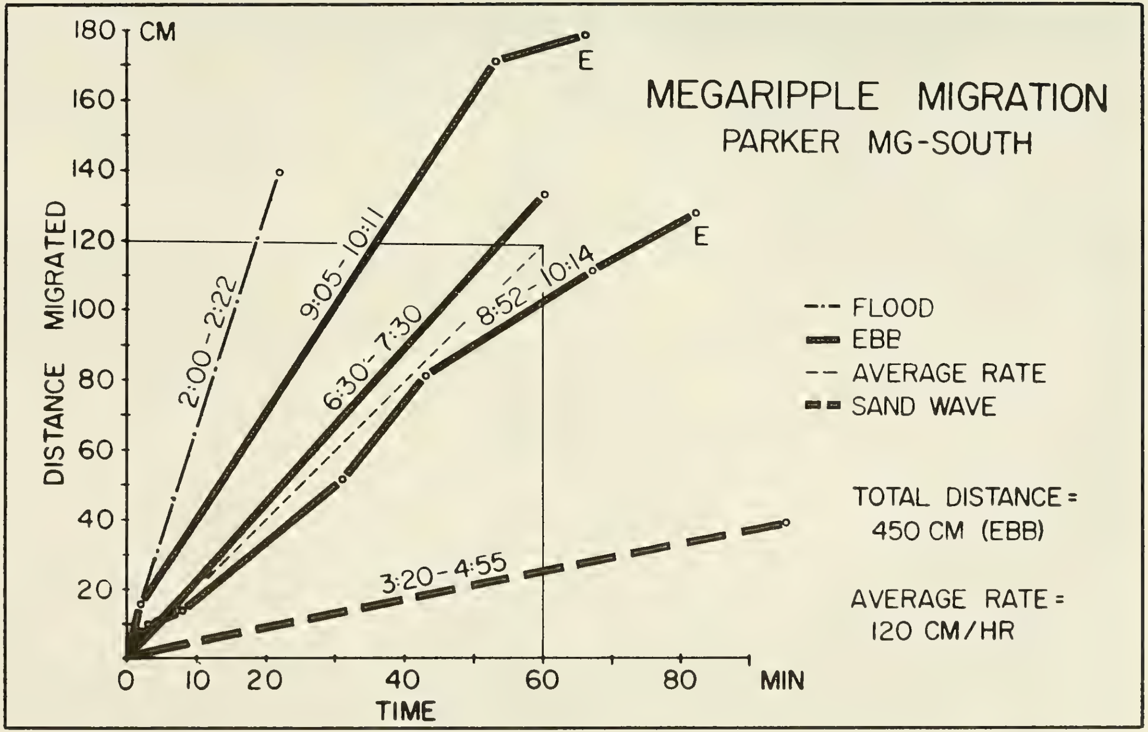


Figure 16. Megaripple and Sand Wave Slipface Migration Rates. (Parker, Middle Ground-South.) Megaripple plots are for parts of the flood and ebb cycle indicated by total elapsed time figures on the graph. The sand wave plot represents an entire tidal cycle. Average megaripple migration rate is 120 centimeters per hour; sand wave rate is 40 centimeters per tidal cycle.

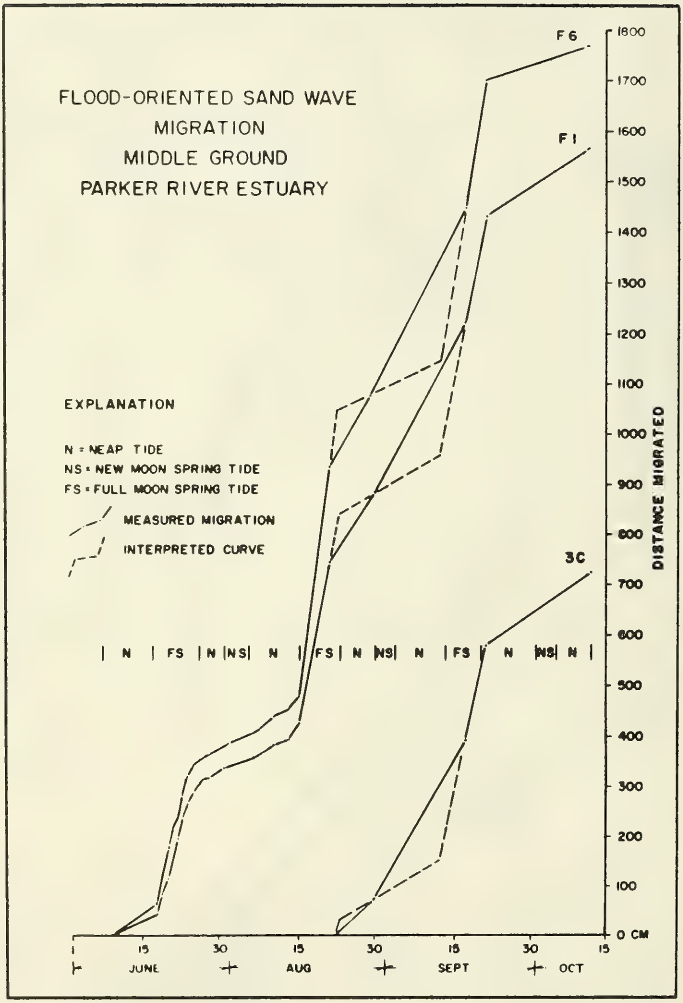


Figure 17. Flood-Oriented Sand Wave Migration, Middle Ground Flood-Tidal Delta, Parker Estuary. Plots indicate distance of slipface migration, at any given date, from a permanent marker stake. The curves show that major slipface migration occurs during full-moon tides.

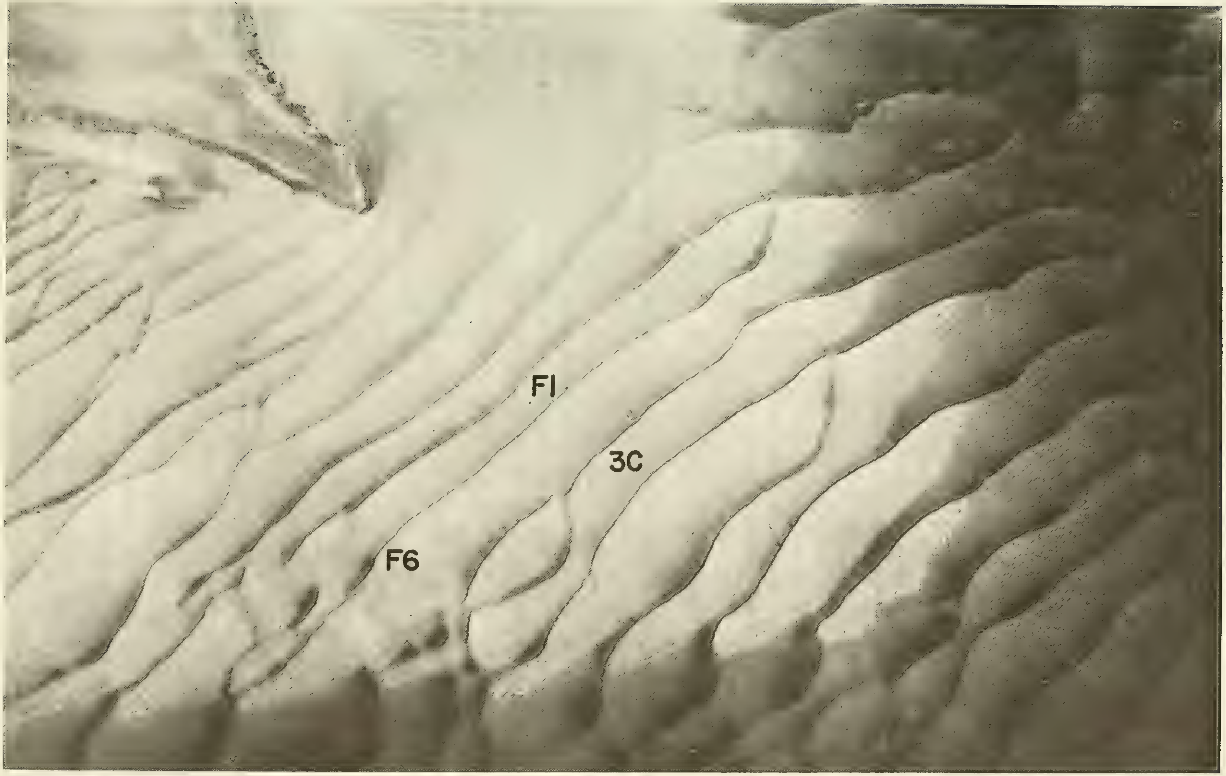


Figure 18. Vertical Aerial View of Intertidal Flood-Oriented Sand Waves on the Southeast Part of Middle Ground. Note position of the long-term migration stations (Figure 17). Spacings of the sand waves are 10 to 15 meters.

VI. BED FORM SEQUENCE

This study of flow conditions and bed form morphology has led to the recognition of a sequence of intertidal estuarine bed forms based on increasing *flow strength*, with velocity as the major contributing parameter. This sequence, shown in Figure 19, is a modification of an earlier version (Boothroyd, 1969), differing mainly in terminology. The sequence may be compared to that of Simons, Richardson, and Nordin (1965), shown at bottom of figure.

The sequence begins with linear ripples and goes to cuspate ripples, termed *low- and high-energy ripples* by Harms (1969). The sequence continues to linear megaripples, which may be transition bed forms. Increasing flow strength causes a change to cuspate megaripples with well-developed scour pits and then to planed-off megaripples. Planed-off megaripples are of two types: 1) short spacings analogous to washed-out dunes of Simons, Richardson, and Nordin (1965); and 2) long spacings which plot near the 6-meter boundary in Figure 11. Rhomboid megaripples, the last form in the sequence, show little slipface development and are essentially a plane bed form. These bed forms were discussed by Smith (1971). Sand waves represent an end member on a separate branch at lower flow strengths.

A plot of velocity versus log-depth (Figure 20), similar to those of Southard (1971), delineates fields where each member of the sequence of bed forms occur. Since unsteady flow conditions occur throughout the tidal cycle, bed form morphology is constantly changing and a given bed form may be stable only during a part of the tidal cycle. Diver observation of bed form changes was used to establish field boundaries. Most measurements in Figure 20 were for water depths greater than 20 centimeters ranging up to 300 centimeters.

VII. INTERTIDAL BED FORM ORIENTATION AND DISTRIBUTION PATTERN

Complex intertidal and subtidal topography controls bed form type and orientation on tidal deltas. Figure 12 illustrates bed form distribution on the intertidal part of the Parker estuary flood-tidal delta; Figure 21 gives bed form orientation on a part of the flood-tidal delta. (Compare Figure 16 with Figure 8.) Megaripples occur on low-intertidal ebb shields subject to high-velocity flood-and-ebb flow. Flood-oriented sand waves occur in areas shielded from ebb flow, and transition bed forms occur in partially shielded areas high on ebb shields and in shallow channels.

Bed form orientations at low water show a strong bimodal pattern (Figure 21.) Sand waves remain flood-oriented throughout the tidal cycle, while megaripples and transition bed forms become alternately flood- and ebb-oriented. Figure 21 shows the tight class-interval grouping by sand waves and the more diverse megaripple and transition bed form pattern.

VIII. SUBTIDAL FLOW CONDITIONS AND BED FORM ORIENTATION

In subtidal channels, bed form type and orientation is controlled by complex intertidal and subtidal topography. Figure 22 shows a longitudinal and a transverse bottom profile of subtidal and intertidal topography and the nature of flood versus ebb channels. (see Figure 12 for profile locations).

Tidal-current velocity curves for two subtidal stations on the flood-channel profile are shown in Figure 23. The curves are similar in maximum flow velocity and flood asymmetry. Their is also a similarity to the velocity curve of the flood-oriented intertidal sand waves. (Figure 14.) Therefore, flood-oriented sand waves, shielded from ebb flow, are similar in morphology, migration habit, and crossbed type whether in depths of 7 meters (MLW), less than 2 meters (MLW), or intertidal.

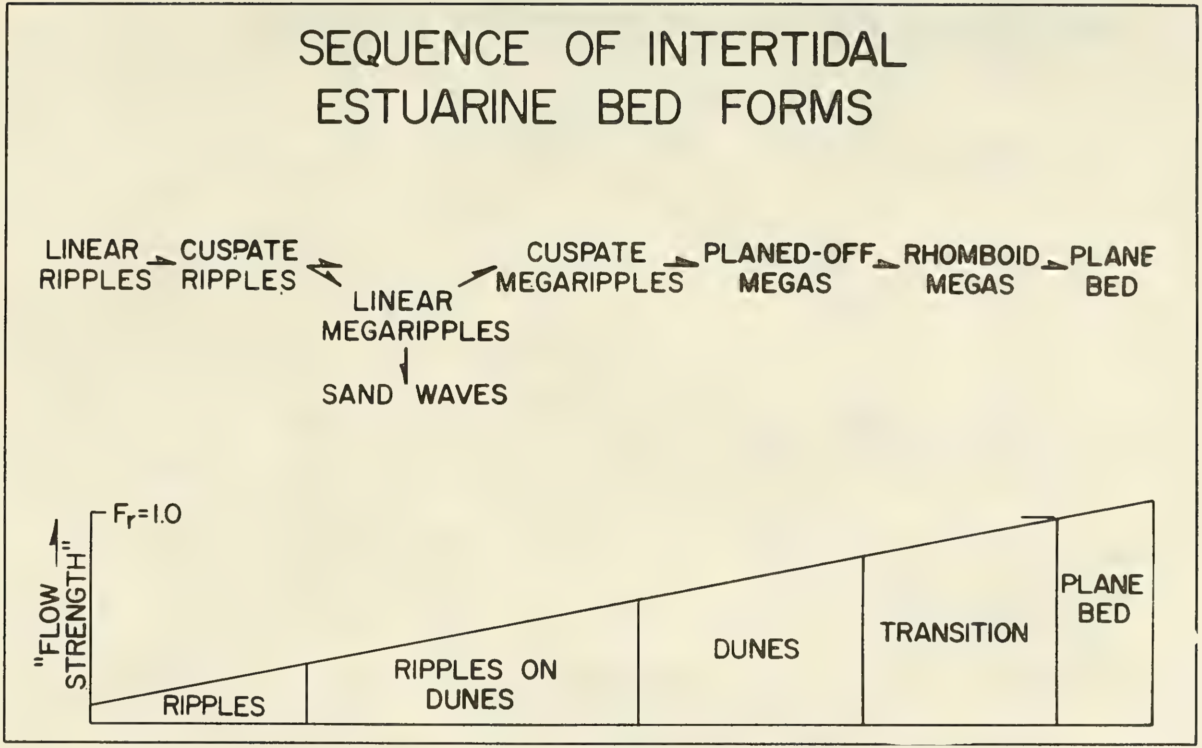


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Figure 19. Sequence of Intertidal Estuarine Bed Forms Based on Increasing "Flow Strength" (modified from Boothroyd, 1969). For comparison, the flow regime sequence of Simons, Richardson, and Nordin (1965) is shown below.

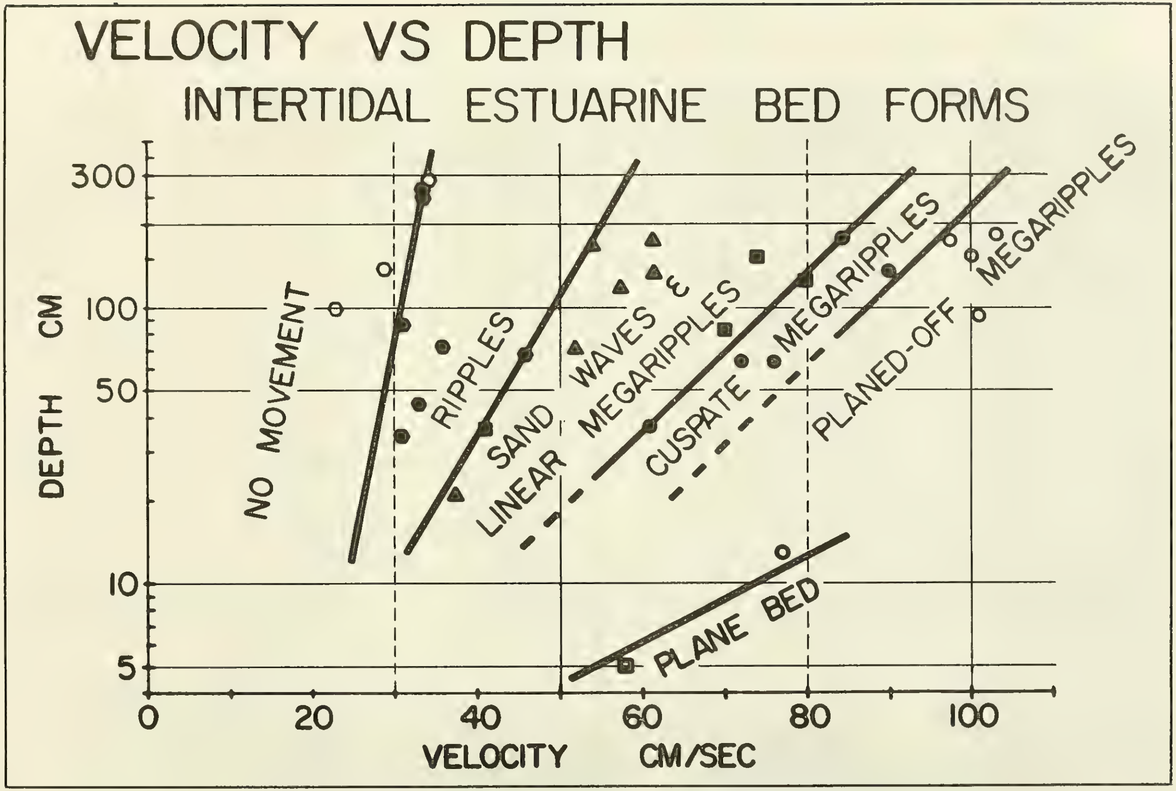


Figure 20. Velocity Versus Log-Depth Plot of Intertidal Bed Forms in Estuaries. Field boundaries were delineated by diver observation of bed form changes under nonuniform flow conditions.

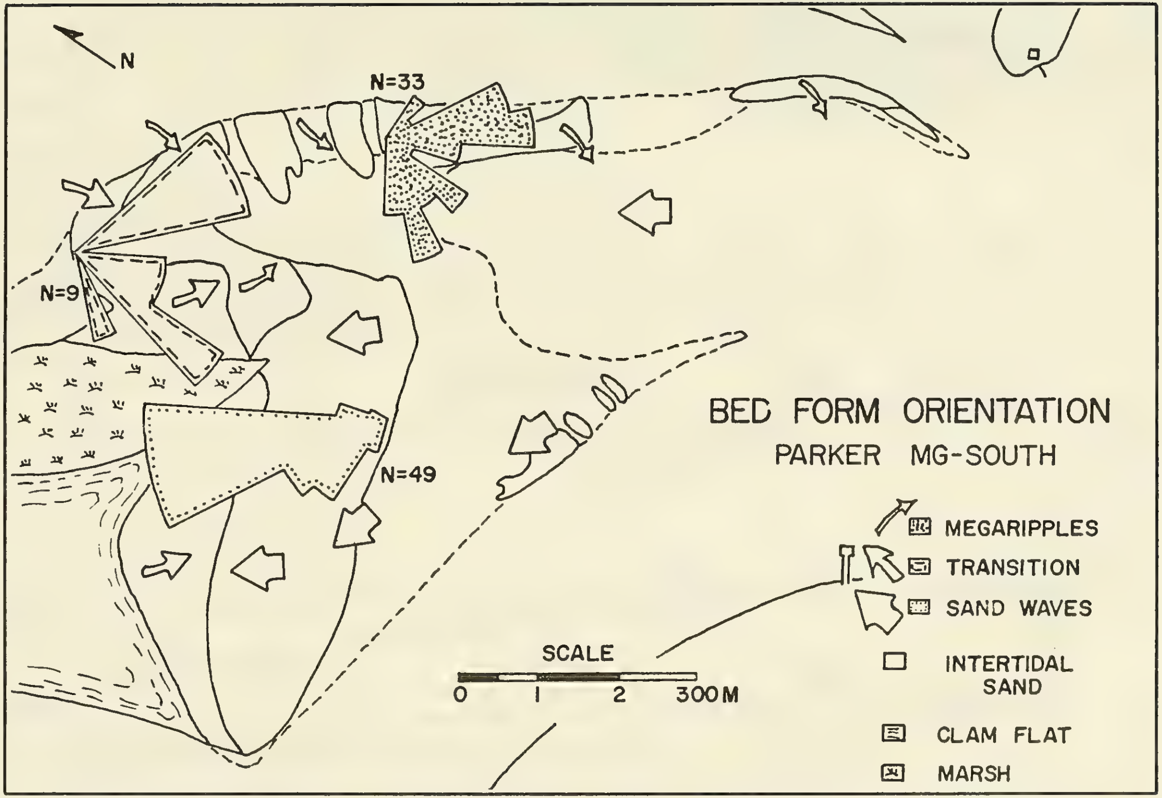


Figure 21. Slip Orientation of Major Intertidal Bed Forms, Middle Ground Flood-Tidal Delta, Parker Estuary. Orientation readings were obtained on a 50-by 50-meter grid system.

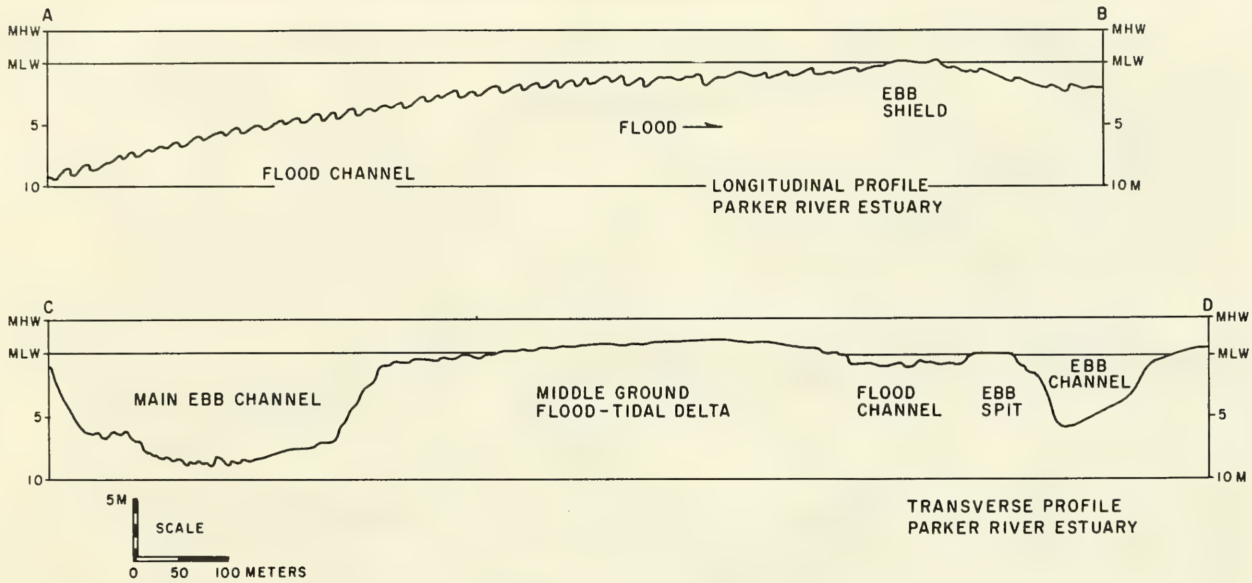


Figure 22. Bottom Profiles of Bed Form Morphology and Sand Body Geometry, Middle Ground Flood-Tidal Delta, Parker Estuary. Profile locations are plotted on Figure 12.

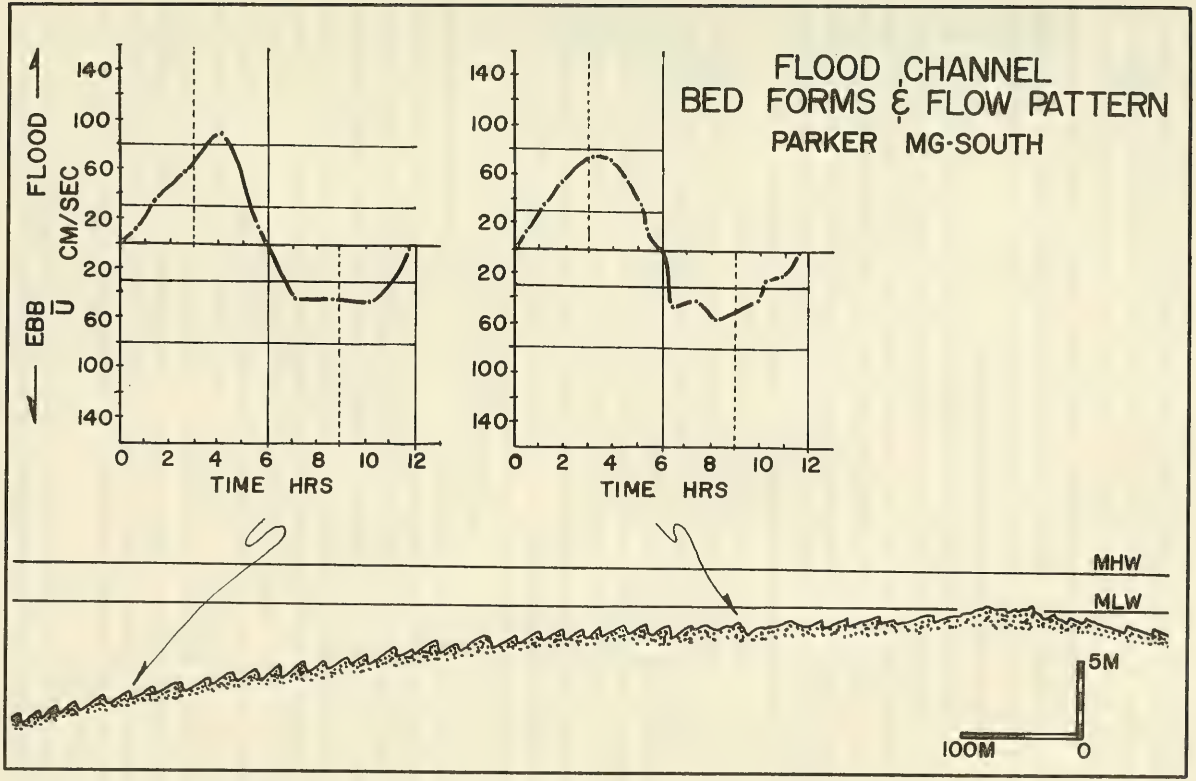


Figure 23. Bottom Profile of a Subtidal Flood Channel Seaward of the Middle Ground Flood-Tidal Delta, Parker Estuary. Note similarity of the sand wave morphology and the tidal-current velocity curves.

In deep ebb channels carrying a large volume of ebb-tidal flow, velocities are high, up to 200 centimeters per second, but the dominant bed forms are sand waves. (Figure 24.) Where velocity asymmetry is low (Station A-3, Figure 24), the sand waves are nearly symmetrical but where velocity asymmetry is high, the sand waves are ebb-oriented. (Station BR-N, Figure 24). Diver observation confirms that when average velocity exceeds 80 centimeters per second, megaripples are superimposed on the sand wave form. Planed-off megaripples are common at these high velocities, including regressive ripples, and ripples migrating transversely down troughs and across sand-wave slipfaces.

Figures 25 through 28 summarize sand movement at Station 2, the symmetrical sand wave station. Major sand movement is by megaripple migration. During the flood-tidal cycle, megaripples migrate up to the sand wave crest and deposit sand on the avalanche slipface of the sand wave. (Figures 25 and 26). During the ebb-tidal cycle, the flood-oriented slipface of the sand wave is modified by ebb megaripple migration up and over the slipface. (Figures 27 and 28.) Net migration of the sand wave slipface was 16 centimeters in the flood direction, illustrating that tidal-current flow at this station is slightly flood-asymmetric.

IX. SUMMARY OF BED FORM DISTRIBUTION

The bed form distribution pattern of the Parker estuary flood-tidal delta shown in Figure 29 is based on 35 kilometers of bottom profiles and diver observation. These data show that megaripples occur on ebb shields, sand waves on large inclined areas seaward of the shields, and transition bed forms in imperfectly shielded areas. Deepwater sand waves, flood- or ebb-oriented, with superimposed megaripples, occur in channels around the tidal-delta wedge. The same orientation pattern occurs in the Essex estuary. (Figure 30.)

In the lower Parker estuary (Fig. 31) deepwater sand waves are the principal bed form except where shallower depths lead to exclusively megaripple formation.

X. CONCLUSIONS

1. Bed forms are classified by spacing and not height. Ripples have spacing less than 60 centimeters; megaripples 60 centimeters to 6 meters; and sand waves greater than 6 meters.

2. Average velocity curves show that megaripples are associated with a high maximum flow velocity and little or no velocity asymmetry; sand waves have a lower maximum velocity and high-velocity asymmetry. A third bed form type, transitional in spacing between megaripples and sand waves, is associated with tidal-current flow of lower maximum velocity than megaripples and little velocity asymmetry.

3. Megaripples migrate in both flood- and ebb-current directions; most intertidal sand waves migrate in a flood direction and do not migrate during ebb flow. Sand wave and megaripple slipface migration begins at about 60 centimeters per second, but flow over megaripples reaches a higher maximum velocity for a longer timespan. Maximum sand wave slipface migration is during full-moon spring tides (40 centimeters per tidal cycle) but is 10 to 50 times less than megaripple migration rates (450 centimeters per tidal cycle in either flood or ebb direction).

4. A sequence of bed forms based on increasing flow strength, with velocity the most important parameter, has been established. (Figure 14.) Velocity–depth plots may be used to delineate fields where each member of the sequence occurs.

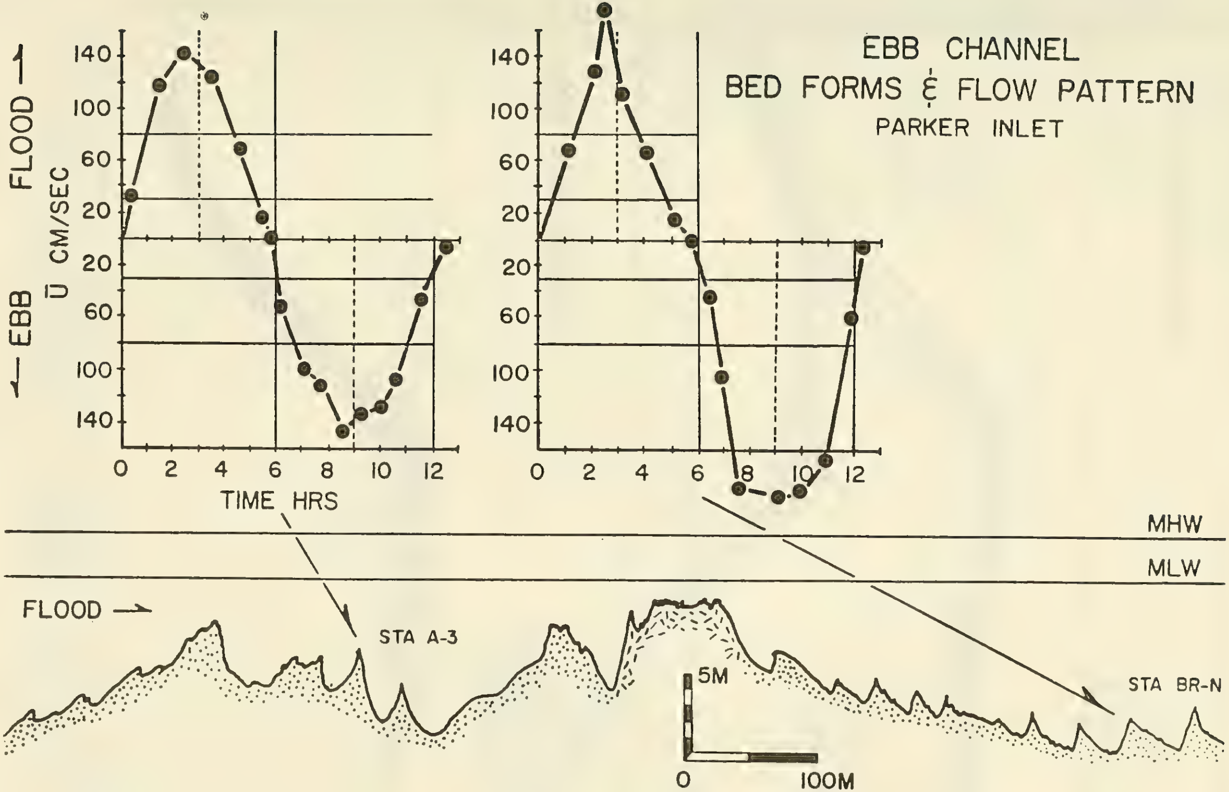
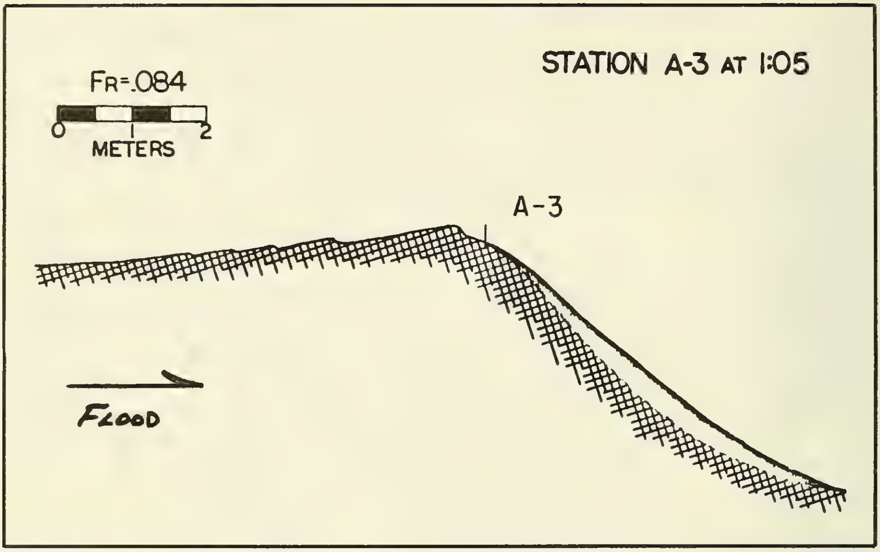


Figure 24. Bottom Profile of a Deep Subtidal Channel Near Mouth of Parker Inlet. The profile line is located on Figure 2. Note the high maximum velocity of both curves.



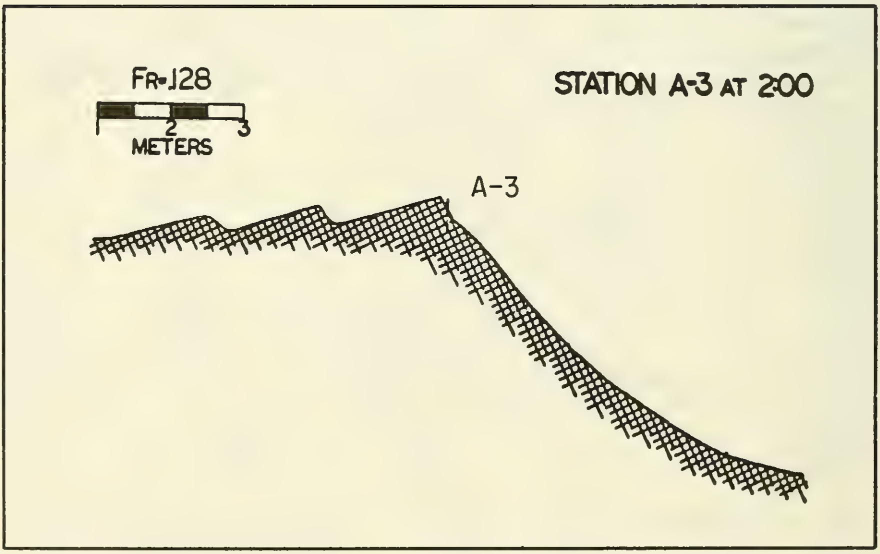


Figure 25. Bottom Configuration at Station A-3 During Flood-Tidal Cycle. Small bed forms are megaripples. Times refer to hours in the tidal cycle.

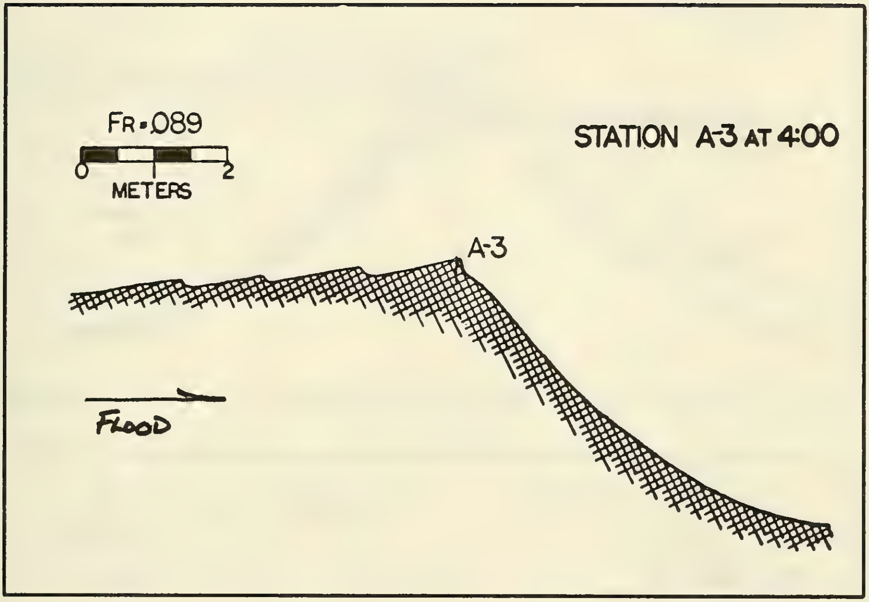


Figure 26. Bottom Configuration at End of Flood Cycle. Sand wave slipface migration was 16 centimeters.

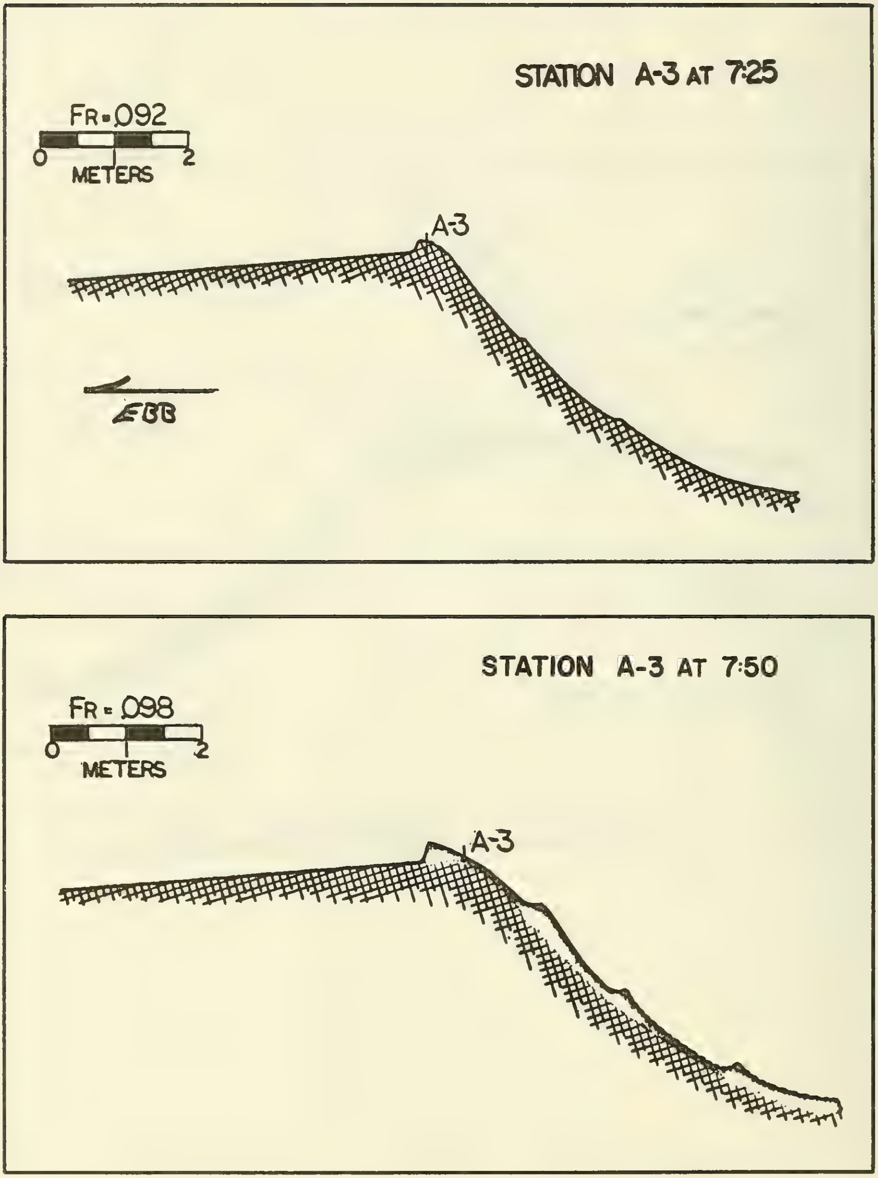


Figure 27. Bottom Configuration During Ebb-Tidal Cycle. Note the megaripple migration up the sand wave slipface.

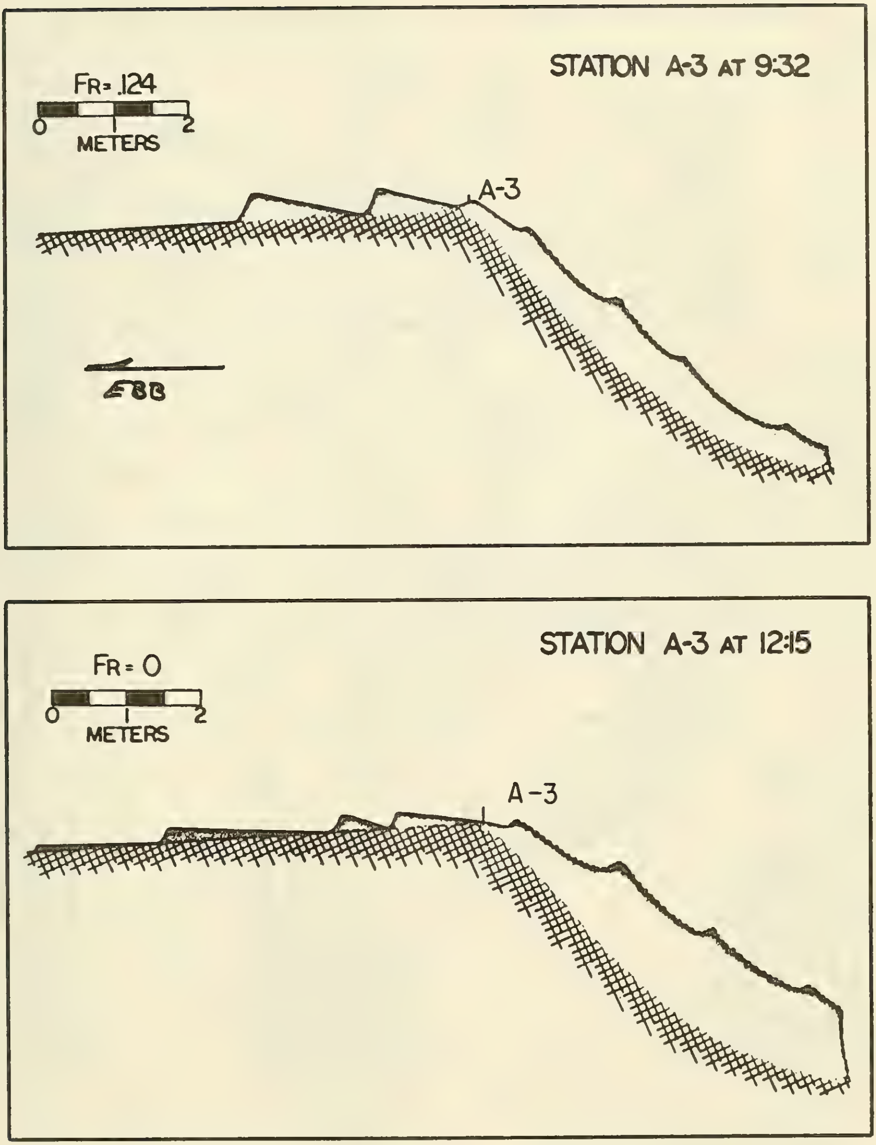


Figure 28. Bottom Configuration During Ebb-Tidal Cycle. Note that the general form of the sand wave is preserved, although its surface morphology is greatly modified.

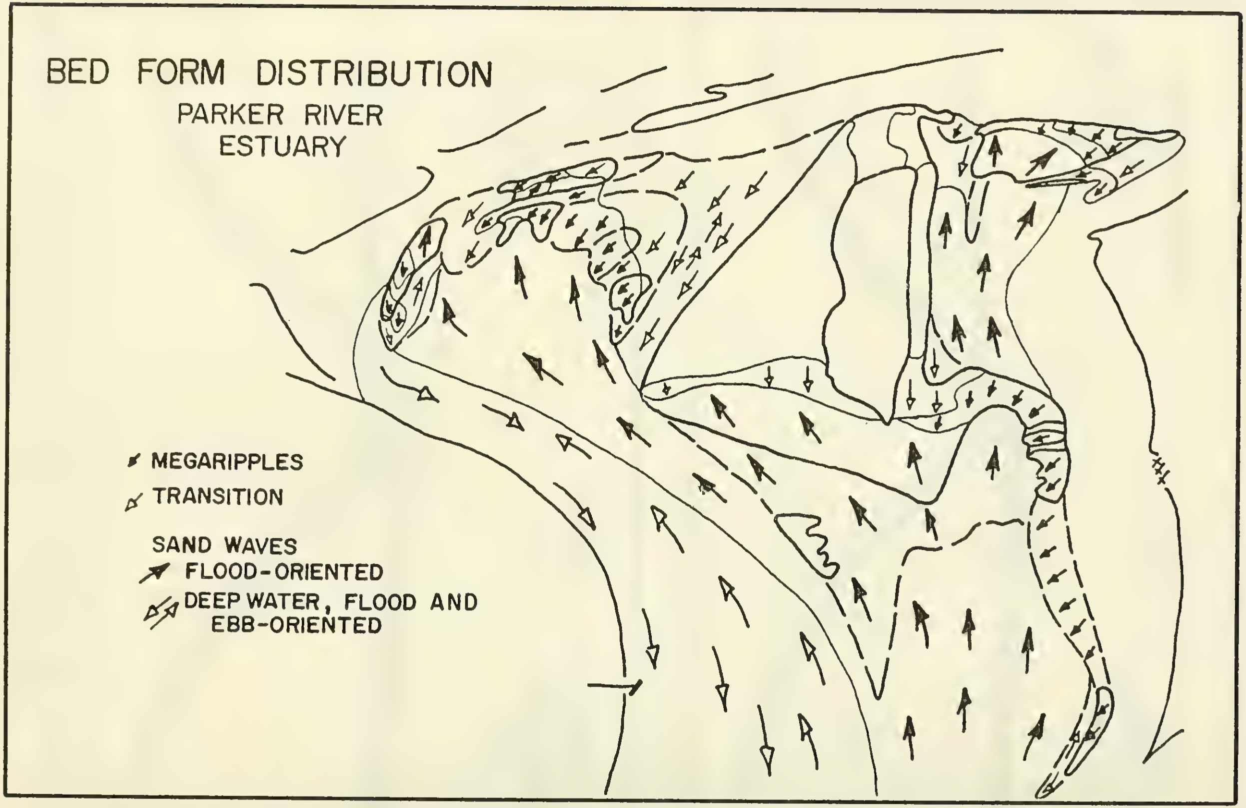


Figure 29. Bed Form Distribution, Parker River Estuary Flood-Tidal Delta. Compare this sketch with the aerial photo in Figure 3.

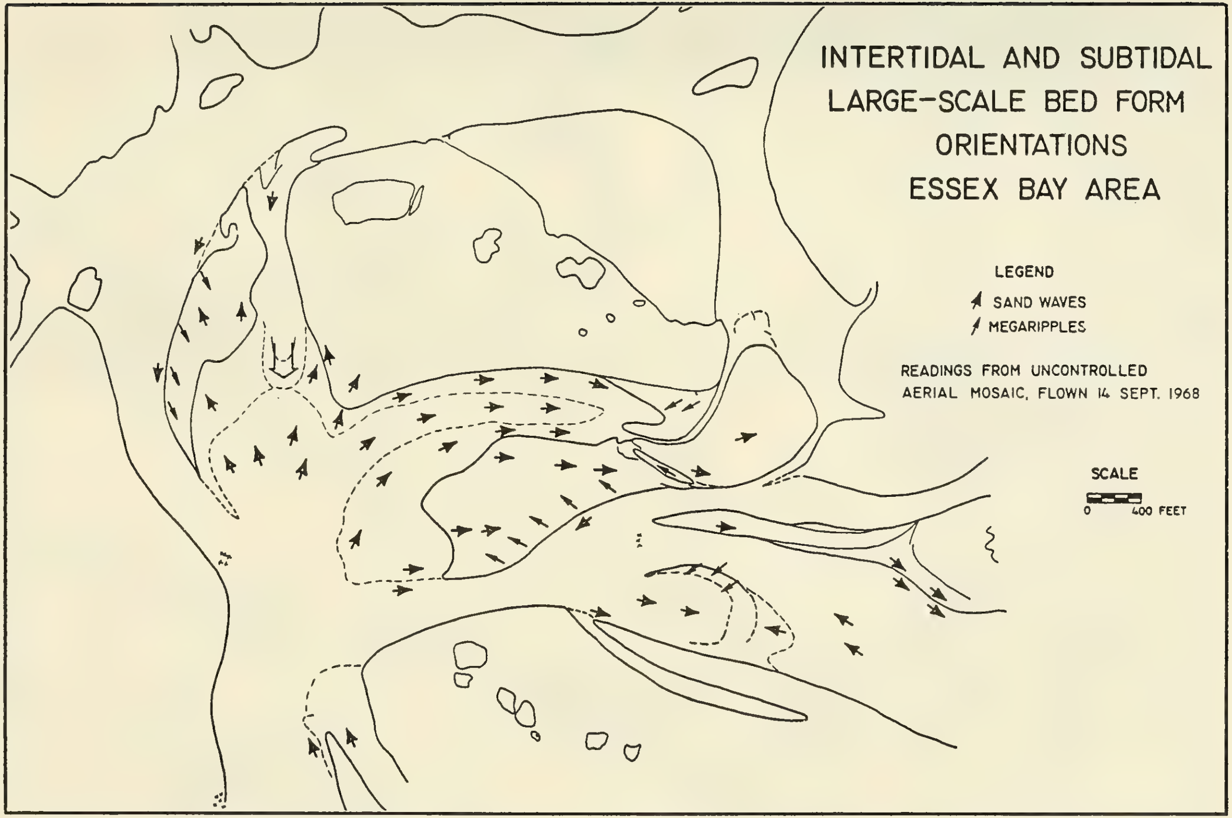


Figure 30. Bed Form Distribution on the Essex Estuary Flood-Tidal Delta. Compare with aerial photo in Figure 4.

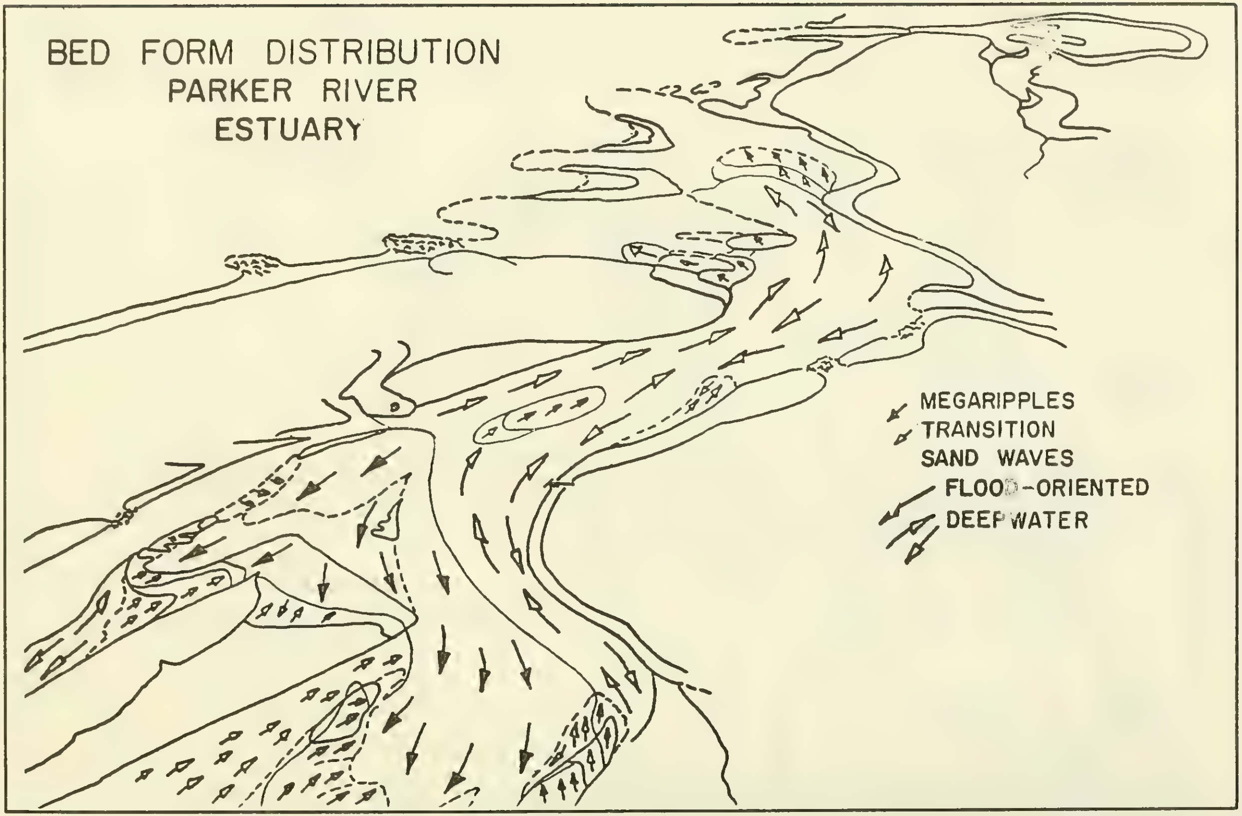


Figure 31. Bed Form Distribution in the Lower Parker Estuary. The most prevalent bed forms are deepwater sand waves. Compare with aerial photo in Figure 2.

5. Complex intertidal and subtidal topography controls bed form type and orientation. On tidal deltas, megaripples occur on low intertidal ebb shields. Flood-oriented sand waves occur in places shielded from ebb flow and transition forms occur in partly shielded areas high on ebb shields or in shallow channels. In subtidal areas megaripples are superimposed on the sand wave form where average velocity exceeds 80 centimeters per second. Deepwater sand waves may be flood- or ebb-oriented, depending on the nature of current velocity asymmetry over the bed form (i.e., flood asymmetry yields flood-oriented sand wave slipfaces).

6. The barge-rope system enables divers to successfully observe bottom conditions in current velocities up to 150 centimeters per second and depths to 7 meters. The system works best at depths less than 5 meters and at current velocities less than 100 centimeters per second, and in waters with good visibility (e.g., New England Coast).

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